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ABSTRACT

Corrosion of tubing used in black-liquor recovery boilers is a major concern in all pulp and paper mills. Extensive corrosion in recovery boiler tubes can result in a significant safety and environmental hazard. Considerable plant resources are expended to inspect recovery boiler tubing. Currently, visual and ultrasonic inspections are primarily used during the annual maintenance shutdown to monitor corrosion rates and cracking of tubing.
This project is developing guided acoustic waves for use on recovery boiler tubing. The feature of this acoustic technique is its cost-effectiveness in inspecting long lengths of tubes from a single inspection point. A piezoelectric or electromagnetic transducer induces guided waves into the tubes. The transducer detects fireside defects from the cold side or fireside of the tube. Cracking and thinning on recovery boiler tubes have been detected with this technique in both laboratory and field applications.

INTRODUCTION

In the kraft recovery boiler, water-filled tubes constitute the structure of the furnace serving to absorb thermal energy from the furnace. Exposed to combustion on the fireside and filled with pressurized flowing feedwater, recovery boiler wall tubes must withstand large and variable thermal and mechanical stresses. Furnace gas temperatures up to 2500° F combined with the harsh molten salt environment can cause premature corrosion on the outer diameter of the recovery boiler wall tubes.
Extensive damage to recovery boiler tubes can result in a significant safety and environmental hazard. Considerable plant resources are expended to inspect recovery boiler tubing. Currently, visual and ultrasonic inspections are primarily used during the annual maintenance shutdown to monitor corrosion rates and cracking of tubing. If corrosion or cracking is detected, tubing must be repaired or replaced during the shutdown.
Guided acoustic waves have been developed as an inspection technique for tubular members for several years. The feature of this acoustic technique is its cost-effectiveness in inspecting long lengths of tubes from a single inspection point. Recent applications on nuclear steam generators have shown that guided acoustic waves can inspect entire cross-sections of tubes over 100 feet. This technique appears very promising for recovery boiler tube application by expediting annual inspection and possibly providing on-line periodic monitoring of tube integrity. Development of a sensor for monitoring the integrity of recovery boiler tubes during the lifetime of the furnace would allow timely replacement of cracked or corroded tubes.

APPROACH

Guided acoustic waves are launched from a single position and propagate along the axis of the tube for long distances. Waves are reflected where damage, such as cracks or corrosion, occur. Guided waves fill the entire cross-section of the tube with acoustic energy, so flaws located on the coldside, fireside, inner diameter or outer diameter can be detected. Each mode has unique characteristics for wave speed, distribution of energy across the thickness, and sensitivity to loading conditions. A successful technique requires that the proper modes be selectively excited. In practice, a single mode must be excited because multiple modes result in several echoes arriving at different times from the same flaw thereby causing difficulty in interpreting data. For boiler tubes, the mode must propagate with minimal sensitivity to water loading conditions and maximum sensitivity to flaws. To selectively excite modes, sensors are designed to propagate waves at the appropriate frequencies and with proper phase characteristics to control the mode generated in the tube.
Our goal in the development of the guided wave technique for boiler tubes is to serve as a screening tool for two types of defects: circumferential cracks at restraints and wall thinning due to corrosion. Guided waves are meant to detect and locate rather than characterize flaws in boiler tubes. It is difficult to precisely characterize flaws using guided waves; flaw sizes cannot be determined without significant error. Hence, a more effective approach is to screen large areas with the guided wave technique and use conventional, localized techniques such as angled shear wave inspection to derive accurate sizing. For screening, creation of a guided wave baseline data set and monitoring

changes to the baseline data over the tube lifetime would make identification of damage easier than initial testing with no prior information.

SENSOR DESIGN

Numerous guided acoustic wave modes can be excited in the tube. All possible modes of propagation are represented in phase and group velocity dispersion curves. For a tube, the curves are calculated by solving eigenvalues of the wave equation with boundary conditions of free surfaces on the outer and inner diameter of the tubes. The dispersion curves of the first 10 axisymmetric modes of propagation for a 3" outer diameter carbon steel tube with a thickness of 0.210" are shown in Figure 1. Phase velocity (Figure 1A), is the speed of the phase of the guided wave. Group velocity (Figure 1B), different from the phase velocity in a guided wave, describes the speed at which the guided wave "packet" propagates. Phase velocity is important in the design of a guided wave sensor while group velocity is used to identify and locate a defect.

Each point on the dispersion curves is a mode with unique properties. Some modes are sensitive to surface conditions, while some are not. Some modes are more sensitive to corrosion than others. A successful technique relies on exciting modes that maximize sensitivity to the desired flaw (cracking or corrosion). Preferential excitation of the most sensitive modes requires proper sensor design.

The piezoelectric sensor that was designed for membraned boiler tubing is shown in Figure 2. The sensor consists of an array of 12 piezoelectric elements mounted on a solid lucite wedge that covers 120° of a 3" diameter tube. The sensor controls the phase velocity by generating a narrow band of phase velocities around a nominal value obtained from Snell's Law. The range of excitation of the wedge is a constant phase velocity at any frequency. The wedge in Figure 2 excites a phase velocity of 3.1 km/s.

For ideal guided wave mode generation and reception, the sensor would fully encircle the tube. This would produce a purely axisymmetric acoustic energy distribution. However, membranes and adjacent tubes on boiler tubing prohibit this as a design feature. Since the loading angle, the angle contacted by the sensor, is restricted to only part of the circumference, the energy distribution is nonaxisymmetric. Maximizing the loading angle makes the acoustic energy more axisymmetric and optimizes generation and reception. Hence, the sensors were designed to maximize the circumferential loading angle without adjacent tubes interfering with placement of the sensors. A more detailed analysis of sensor design can be found in [1,2].

EXPERIMENTAL RESULTS

Experimental tests were conducted on a variety of samples with both simulated flaws as well as real defects. In these tests, the piezoelectric array sensor in Figure 3 both sends and receives the guided waves and detects defects in reflection mode. A tone burst generator, capable of sweeping through frequencies, is used to excite the sensor.

Circumferential cracking

Figure 3 shows a section of boiler tube that was pulled out of service due to circumferential cracking. The crack in Figure 3 located at approximately 9" according to the scale is highlighted by dye penetrant. X-ray computed tomography (CT) was performed on this section to obtain an image of the crack. Circumferential X-ray CT slices of the inner and outer diameter in Figure 4 show that the crack initiated on the I.D. and grew to the O.D. To test guided wave detection on this type of crack, the 12" section of tube was then welded between two - 10' lengths of tubes according to industry welding guidelines.

A guided wave signal detecting the crack is shown in Figure 5. The tone burst excitation frequency was tuned to 510 kHz to maximize the reflection from the crack. Reflections from the welds also appear before and after the crack reflection. A reflection from the end of the tube, 16 ft. away, also appears in the signal. The results demonstrate long-distance detection of a real circumferential crack by the guided wave technique.

Simulated thinning near a welded attachment

Another test was performed on a mockup set of tubes to show the ability to resolve flaws in the vicinity of attachments. Thinning was simulated near an attachment by machining a 1" x 1" area to a depth of 0.066", or 30% of the thickness, into a tube near an attachment. The welded attachment area is shown in Figure 6.

The tube in Figure 7 was tested using the guided wave technique with the sensor approximately 40" from the thinning and attachment. The simulated thinning was easily detected in reflection mode as shown in the guided

wave signal in Figure 7. Detection of the thinning was verified by group velocity calculations of the mode as well as damping the signal on the tube around the thinning.

Stress-assisted corrosion in tangent tubes

Tests were performed on panels of tubes having areas suspected of having stress-assisted corrosion (SAC). The panels, as shown in Figure 8, were tangent tubes, 24" in length, 2" in diameter and 0.170" thick. The panels were removed from the sidewall of the boiler above the secondary airports and below the nose arch. Radiographs were taken of the panels to identify tubes with SAC. The depth of the SAC was roughly estimated at about 20% through-wall. The SAC had several orientations. A typical radiograph of the SAC area of a tube is shown in Figure 9.
The tubes had extremely rough surfaces as a result of many years in service. The surfaces were so rough that standard ultrasonic techniques could not be performed because of insufficient coupling. Profilometry using a 2 μm diamond tip stylus showed a 0.030" peak-to-peak variation along the length on the fireside and 0.025" variation on the coldside.
The surfaces of the tangent tubes had to be aggressively cleaned for guided wave testing. The tubes were cleaned in a 4" x 4" area to ensure sufficient sound propagation from the sensor into the tube. The cleaning involved a wire brush and took a similar amount of effort as standard cleaning that is done for annual shutdown ultrasonic inspection techniques.
The tangent tubes demonstrate why extremely low detection sensitivity is not desirable in this application. Sensitivities to wall thinning and other flaws that are much below 10% through-wall would result in the detection of numerous features that are of little interest, e.g. surface roughness, scratches, and general wear. A successful guided wave technique should effectively filter out features that are not of interest. The tangent tubes were rejected for cracking, not for thinning. For these tubes, the technique must detect cracking or deep areas of thinning while not detecting the thousands of small features on the surface. Aggressively cleaning tubes for inspection is time-consuming and at times impractical. Electromagnetic acoustic transducers (EMAT), sensors that modulate a magnetic field to create an acoustic wave, are known to perform well on rough surfaces. For comparison, the tangent tube with SAC was tested using a flat EMAT. The guided wave signal using an EMAT send/receive pair is shown in Figure 10.

CONCLUSIONS

A guided wave technique was developed as a screening tool for wall thinning and cracking in recovery boilers. Detection of both real and simulated flaws was demonstrated on tubes in the laboratory. Water washing and wire brushing were sufficient preparation for the tube surface when using a piezoelectric transducer. The technique could detect defects with a minimum depth of 20% wall thickness. Greater sensitivity may not be desirable because it may result in detection of large numbers of less significant features like scratches or surface roughness. EMAT sensors show potential in minimizing surface preparation.

ACKNOWLEDGEMENTS

REFERENCES

1. Sun, Z., Rose, J.L., Quarry, M.J., Chinn, D.J., "Flexural Mode Tuning in Pipe Inspection," Review of Progress in Quantitative Nondestructive Evaluation, Vol. 21A, pp. 262-269, 2002.
2. Rose, J.L., Li, J., Zhou, X., Quarry, M.J., Chinn, D.J., "Ultrasonic Guided Wave Mode Tuning for Limited Access Tube Inspection," Review of Progress in Quantitative Nondestructive Evaluation, Vol. 20A, pp. 164-171, 2001.
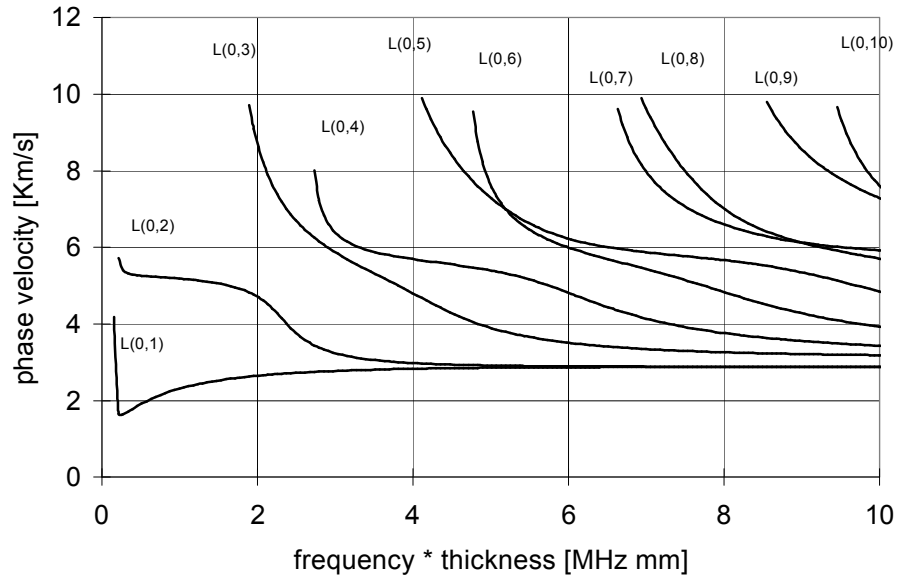
Figure 1A. The first 10 axisymmetric guided wave modes are described by phase velocity dispersion curves for a 3" O.D. carbon steel tube with a thickness of 0.210".
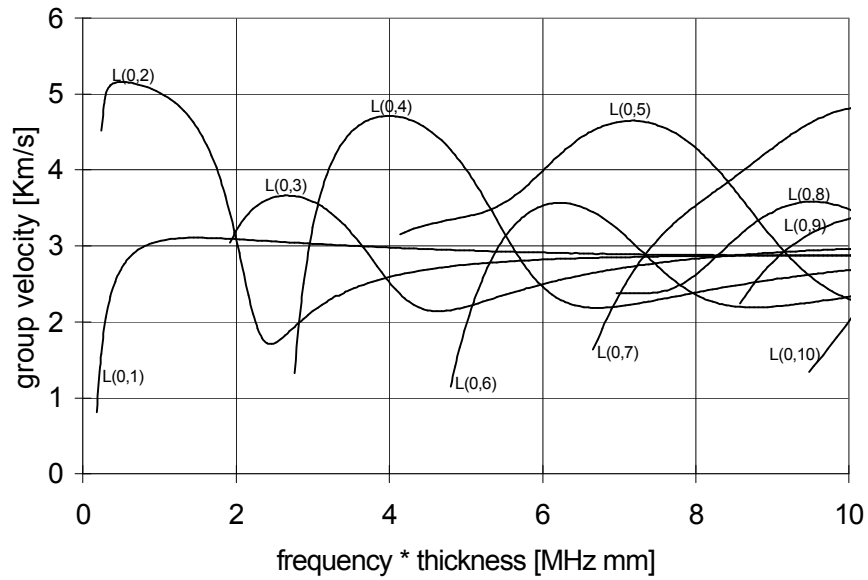

Figure 1B. Group velocity dispersion curves for the first 10 axisymmetric modes in Figure 2A show the velocity of the wave "packet".
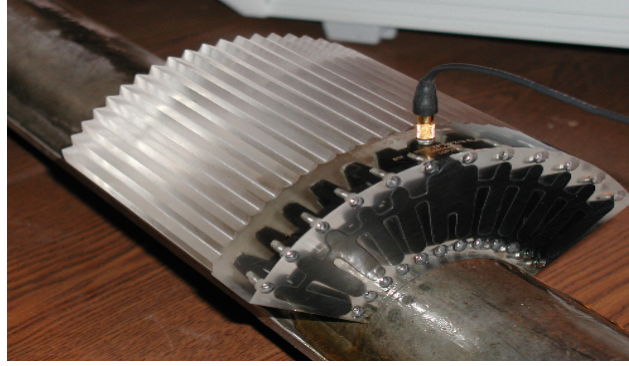
Figure 2. A piezoelectric array sensor for exciting and receiving guided waves in recovery boiler tubing contacts on accessible area of the tube.

Figure 3. A piece of boiler tube was pulled out of service because of a crack, located just beyond the membrane, is indicated by a dye penetrant.

0°   180°   360°
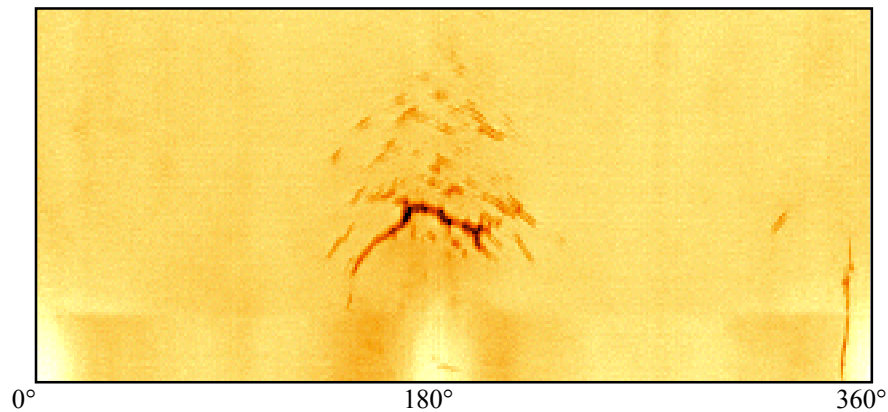
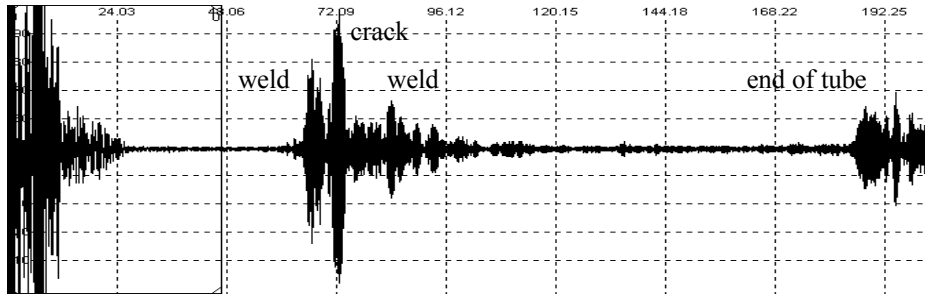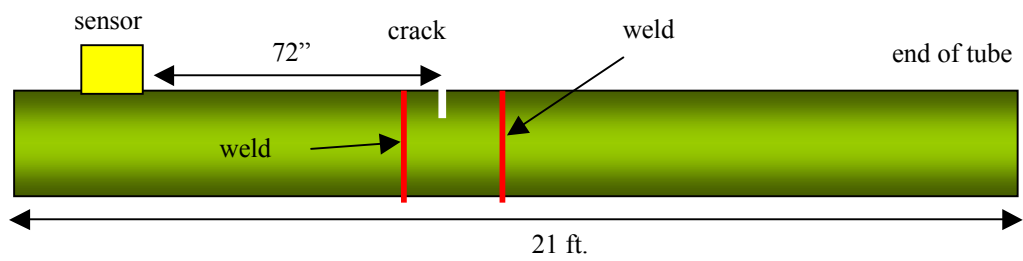Figure 4. X-ray CT image of the inner diameter of the circumferential crack specimen.

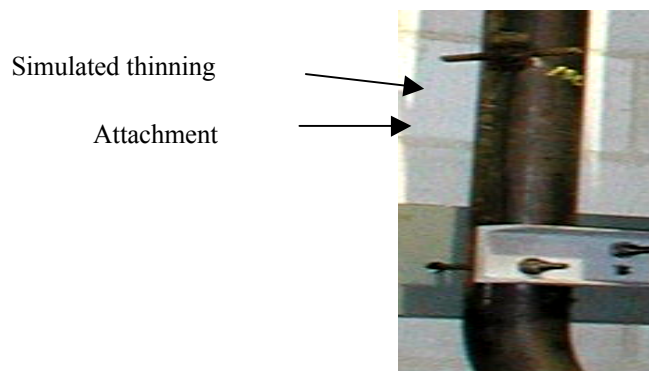Figure 5. A sample RF waveform shows detection of a crack at 72".

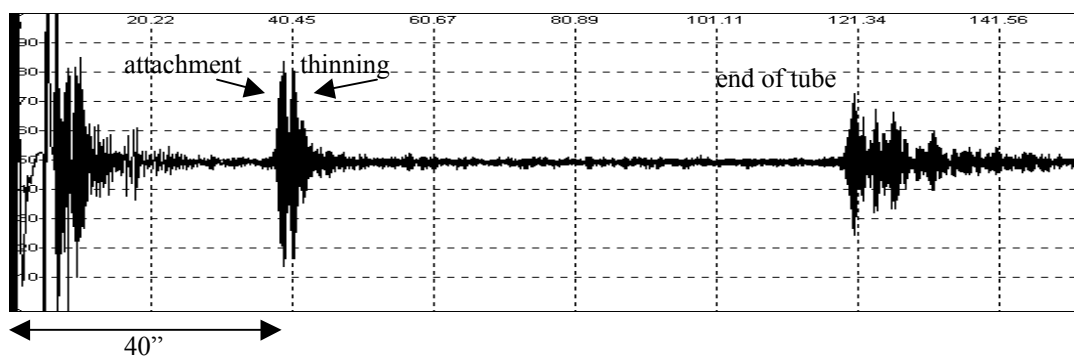Figure 6. A 1" x 1" area of simulated thinning is located near a welded attachment.

Figure 7. A guided wave signal in reflection mode shows the detection of simulated wall thinning near a welded attachment.

Figure 8. A panel of tangent tubes with suspected stress-assisted corrosion was tested with guided waves.
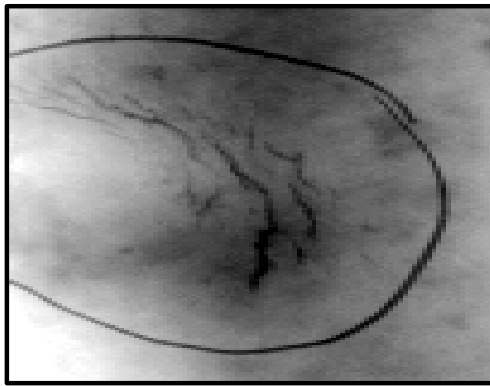

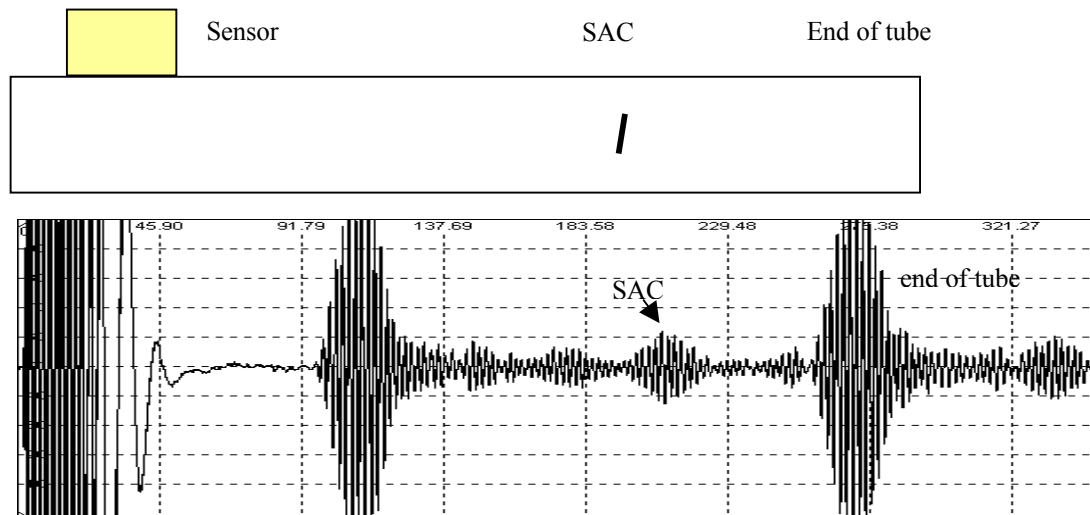Figure 9. A radiograph of a tangent tube shows stress-assisted corrosion.

Figure 10. A guided wave signal generated with EMAT sensors shows detection of SAC.